A Model of Electric Field Assisted Capillarity for the Fabrication of Hollow Microstructures

C. Tonry[1*], M. Patel[1], C. Bailey[1], M.P.Y. Desmuliez[2], S. Cargill[2], W. Yu[3]

[1]Computational Mechanics and Reliability Group (CMRG), School of Computing and Mathematical Sciences

[2]Microsystems Engineering Centre (MISEC), School of Engineering & Physical Sciences,
Heriot-Watt University

[3]State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine mechanics and Physics,
Chinese Academy of Sciences

Excerpt from the Proceedings of the 2012 COMSOL Conference in Milan

UNIVERSITY of GREENWICH

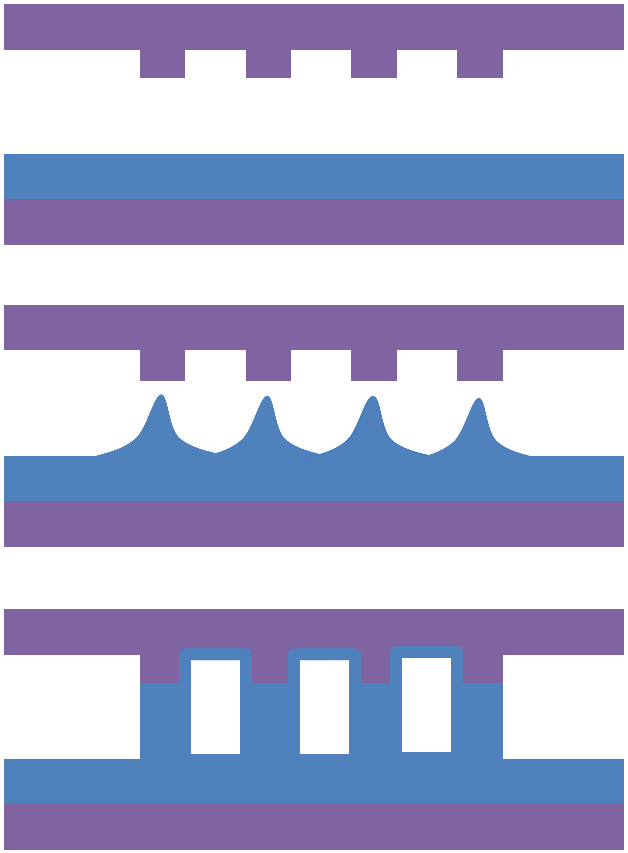
HERIOT WATT UNIVERSITY

Contents

- What is Electric Field Assisted Capillarity(EFAC)?
- Forces
- The Model
  - Interfacial force
  - Geometry
  - Mesh and Material Properties
  - Viscosity
- Results
  - Contact Angle
  - Electric Field
  - Air Gap
  - Comparison to experiment
- Conclusions
- Further Work
- Further Information

What is Electric Field Assisted Capillarity (EFAC)?

- A process which patterns polymers using electric fields
- Polymers must be semi-molten
- Initially surface driven by electric field
- When the polymer reaches the top mask Capillary force becomes dominant
- This causes the polymer to coat the top mask forming a hollow microstructure



Forces

Electrostatic and Dielectric Forces

- These are the dominant force at the start of the process
- They are concentrated around the polymer/air interface
- It is proportional to the square of the electric field

Capillary Force

- This becomes dominant when the polymer reaches the top mask
- As this is due to surface tension it again is concentrated around the air/polymer interface
- This is due to the small contact angle (20-30˚ for PDMS and the mask)

UNIVERSITY of GREENWICH

HERIOT WATT UNIVERSITY

The Model

- Process is modelled using the Lamina Phase Field and Electrostatics modules in COMSOL 4.0/4.2
- The Lamina Phase field module describes the motion of the fluid using Navier-Stokes and the surface using a Diffuse Interface Phase Field model
- The phase field module calculates the surface tension forces
- The Electrostatics module solves for the voltage and calculates electric field from this
- This electric field is then used to calculate the interfacial force due to the electric field

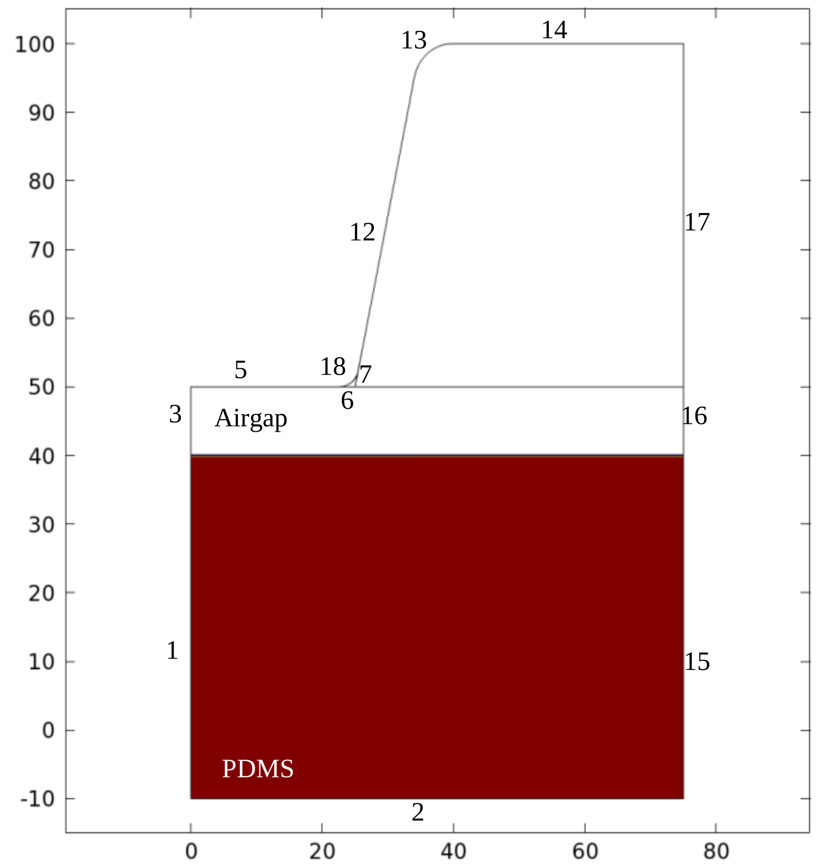
Interfacial Force

- The charge density at the surface is represented by
  $\sigma = (\epsilon_r - 1)\epsilon_0\, \mathbf{E} \cdot \hat{\mathbf{n}}$
- This is derived from the surface charge density in terms of the polarisation:
  $\sigma = \mathbf{P} \cdot \hat{\mathbf{n}}$
- And the Polarisation in terms of the electric field
  $\mathbf{P} = (\epsilon_r - 1)\epsilon_0 \mathbf{E}$
- This equation is then combined with the expression for electrostatic force:
  $\mathbf{F} = \rho_f \mathbf{E} - \frac{1}{2}\mathbf{E} \cdot \mathbf{E} \nabla\epsilon + \nabla(\frac{1}{2}\mathbf{E} \cdot \mathbf{E} \frac{\partial \epsilon}{\partial \rho}\rho)$
- To give an expression for the force per unit area at the interface:

$$\mathbf{F} = ((\epsilon_r - 1)\epsilon_0\, \mathbf{E} \cdot \boldsymbol{\nabla}\phi)\mathbf{E} - \frac{1}{2}\mathbf{E} \cdot \mathbf{E} \nabla\epsilon + \nabla(\frac{1}{2}\mathbf{E} \cdot \mathbf{E} \frac{\partial \epsilon}{\partial \rho}\rho$$

Geometry and Boundary Conditions

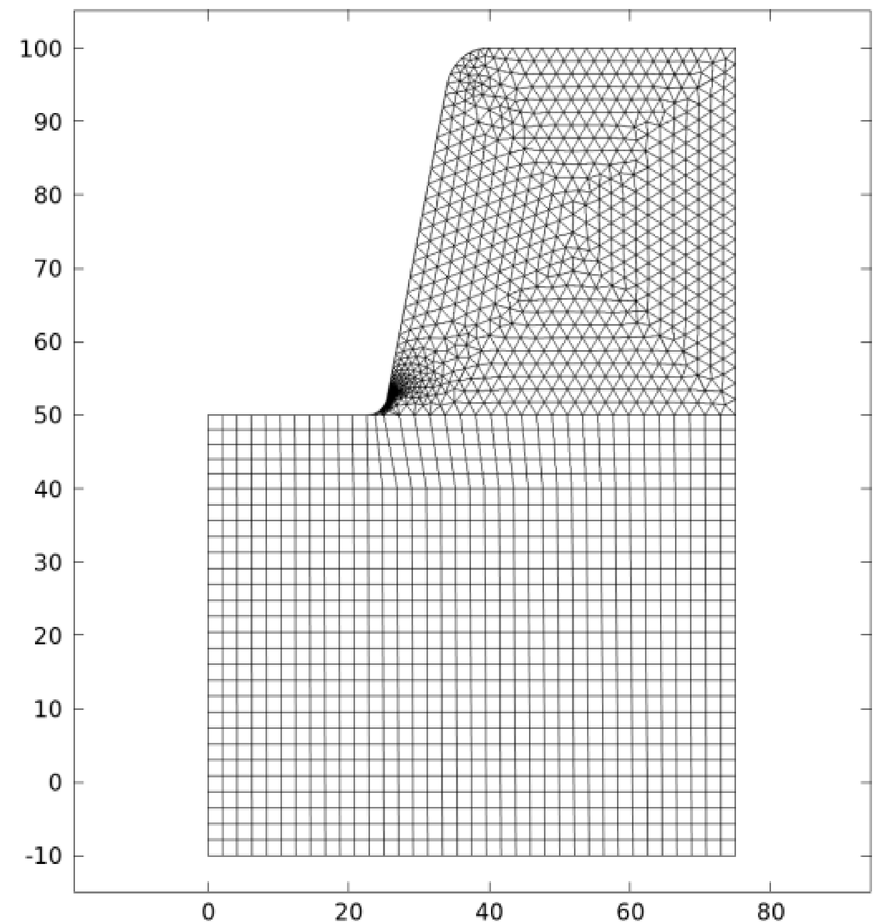
	Flow	Electric Field
1	Slip Wall	Symmetry
2	No-Slip Wall	0V
3	Slip wall	Symmetry
5	Slip wall	300V
6	Wetted Wall	N/A
7	Wetted Wall	N/A
12	Wetted Wall	300V
13	Wetted Wall	300V
14	Wetted Wall	300V
15	Symmetry	Symmetry
16	Symmetry	Symmetry
17	Symmetry	Symmetry
18	N/A	300V



Mesh and Material properties

- Triangular Elements are used in the top part of the mask
- Mapped Quads are used in the lower part
- Material Properties

Simulation Dynamic Viscosity (Centipoise)	Specific Gravity (25℃)	Dielectric Constant (100Hz)	Surface Tension (mN/m)
1000	1.03	2.72	20

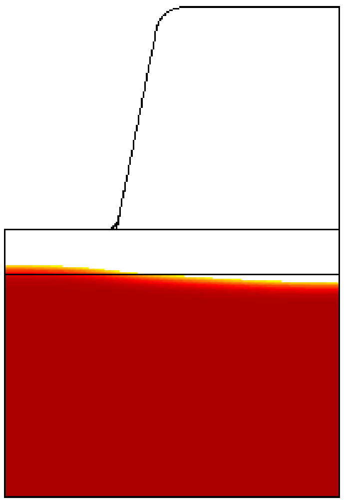


UNIVERSITY of GREENWICH

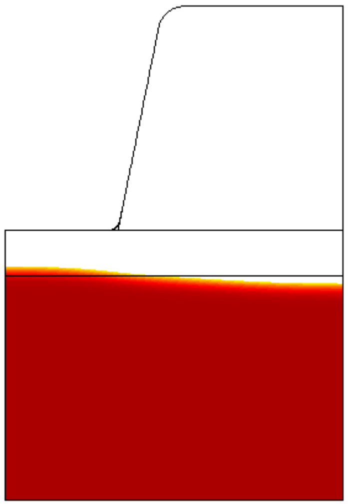
HERIOT WATT UNIVERSITY

Viscosity

- To reduce simulation time a lower viscosity has been used
- These animations compare a 250 cp case to a 1000 cp case
- The final thickness is the same only the simulation time is different



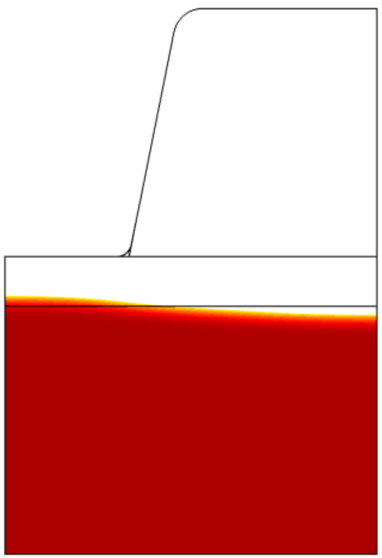
250 cp



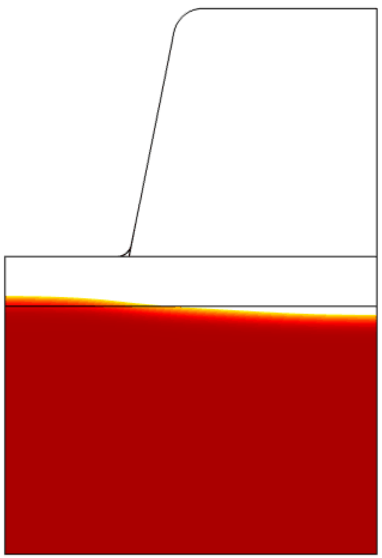
1000 cp

Effect of Contact Angle

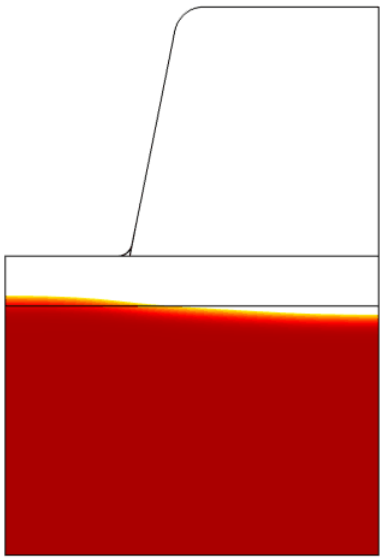
- Increasing Contact angle Decreases Cap Thickness



10º contact Angle



20º contact Angle

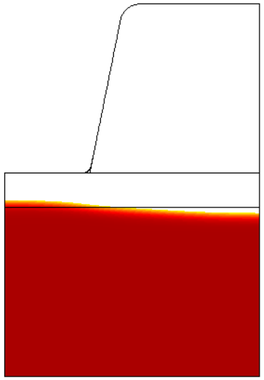


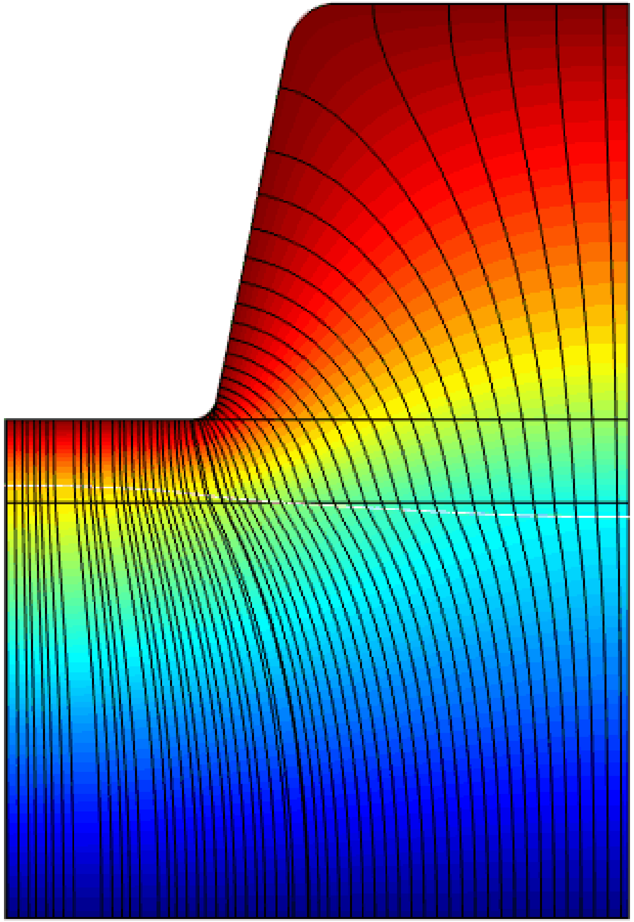
25º contact Angle
Unable to form Complete Cap

- This is probably due to the reduced capillary force

Electric Field

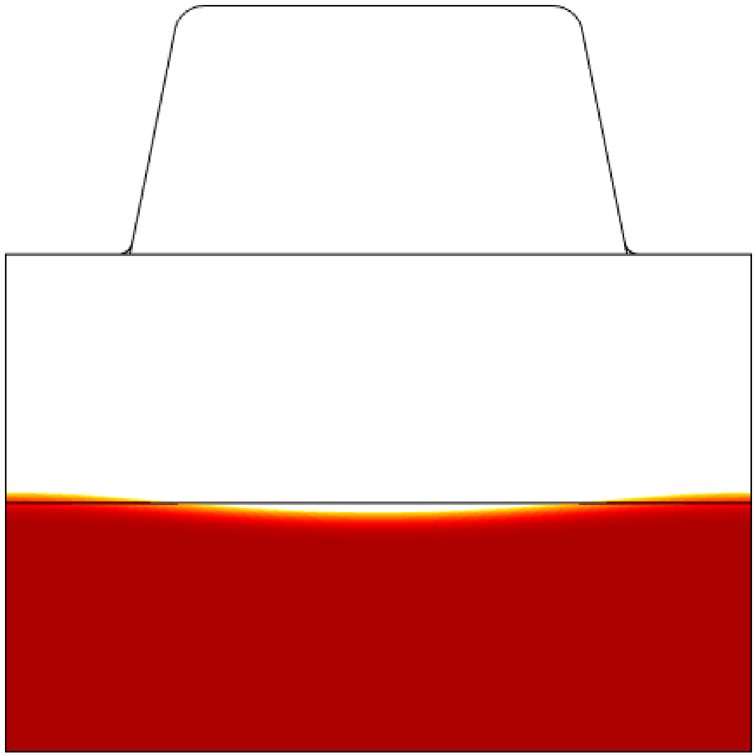
- Electric field at the surface (white line) is higher under the lower part of the mask
- This is what causes the surface to move



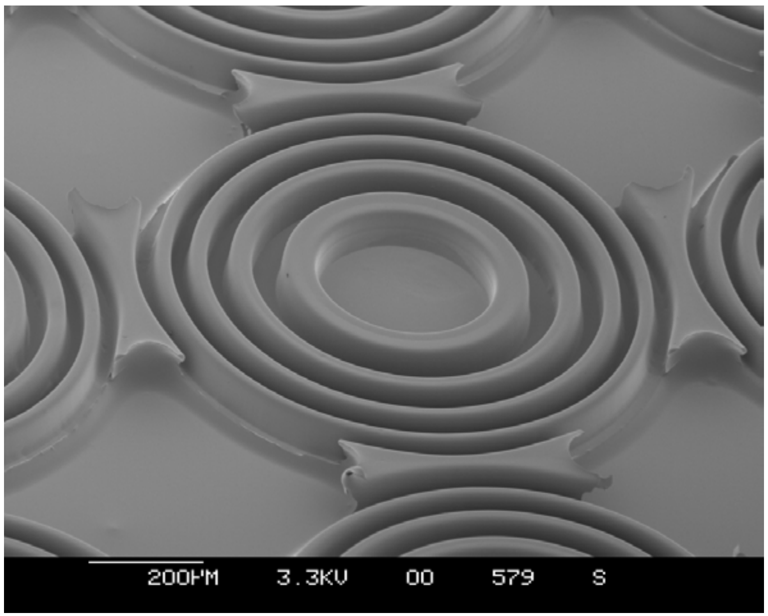


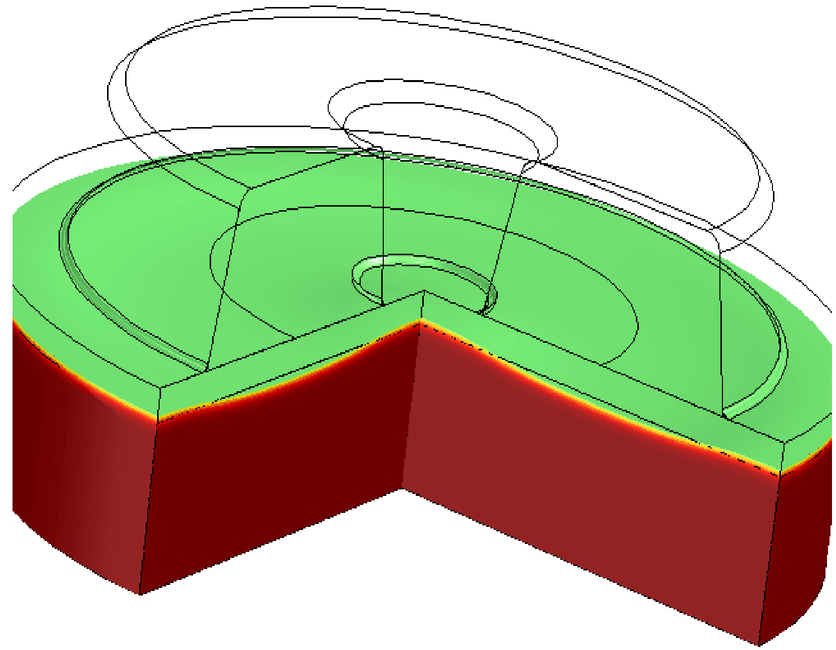
Large Air Gap

- Increasing the Air Gap creates a deeper channel for the same amount of polymer
- Using a wetted surface at the bottom results in a square bottomed channel



Comparison with Experiment





Angled Channel 15º contact Angle
Swept to form a 3D representation

Conclusions

- The model presented here has provided some further avenues for further investigation
- The main one of these in terms of reliability is contact angle which should be alterable by changing the mask properties
- Further work is needed to develop a model including higher viscosities and also incorporating a Oldroyd-B model of the viscoelasticity, to see if this has an effect on the shape of the structures

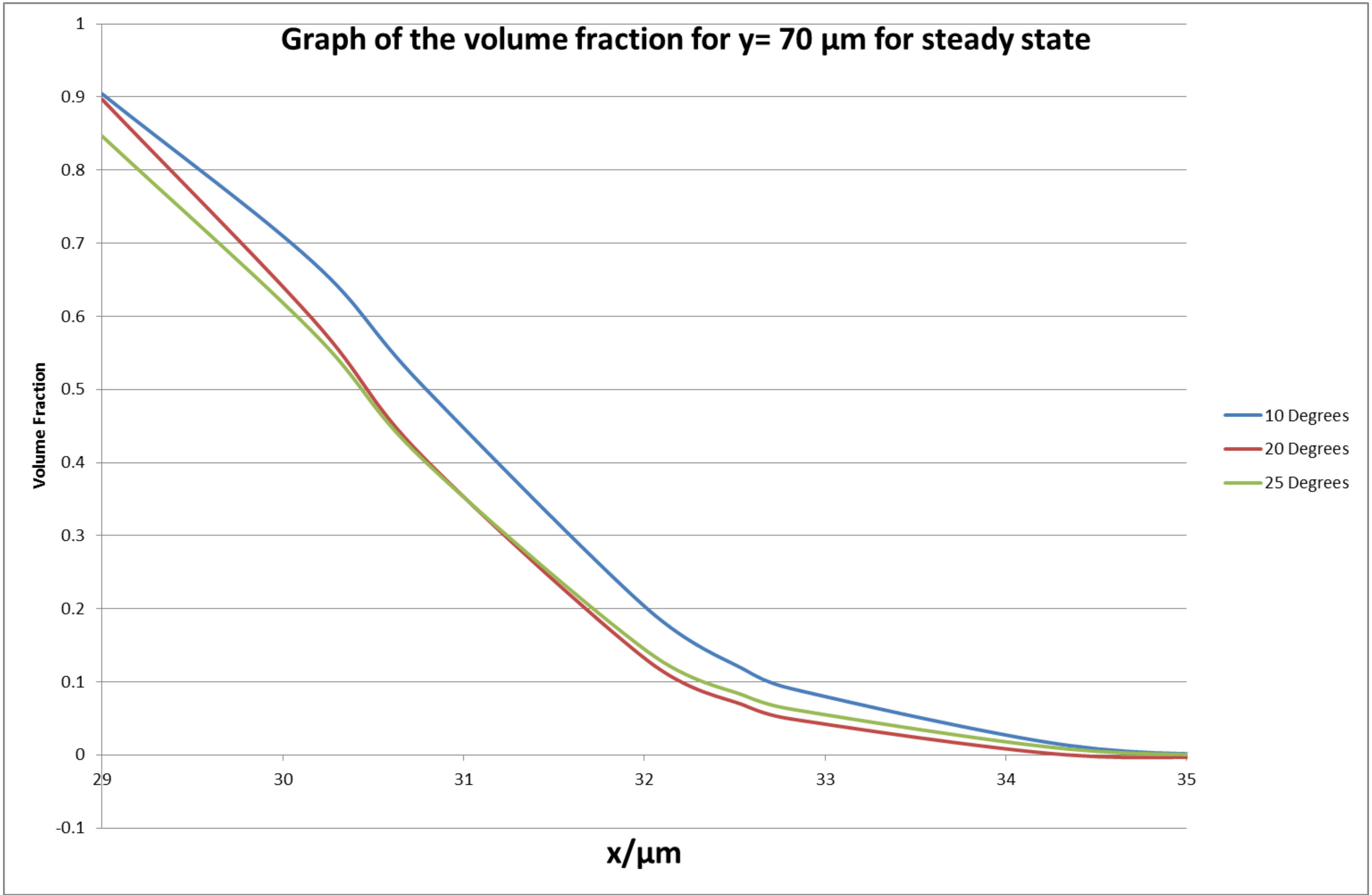
UNIVERSITY of GREENWICH

HERIOT WATT UNIVERSITY

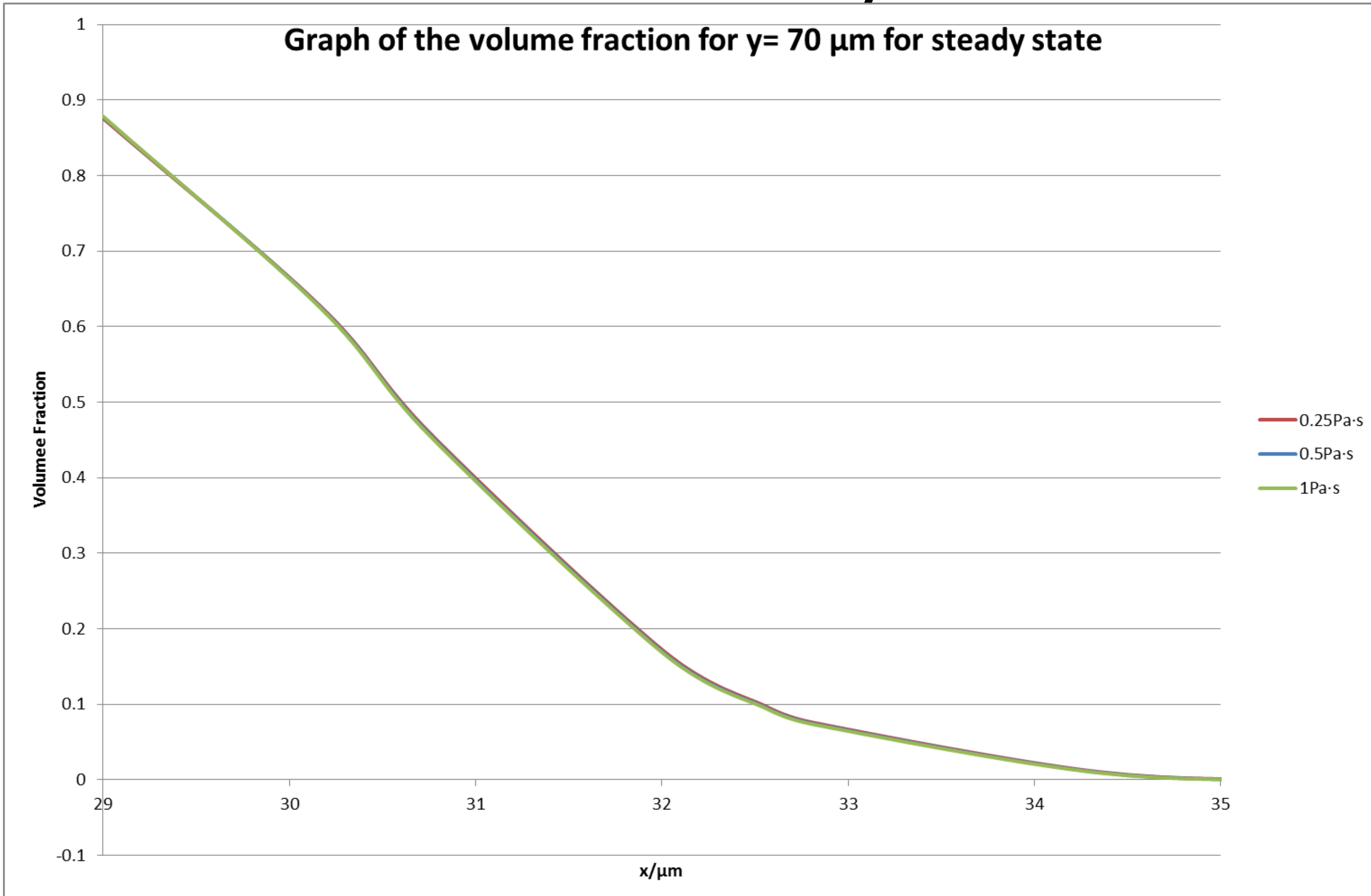
Thank You

Any Questions?

Contact Angle



Viscosity



Graph of the volume fraction for y= 70 µm for steady state
Volumee Fraction
x/µm
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
29
30
31
32
33
34
35
0.25Pa·s
0.5Pa·s
1Pa·s

Viscosity – Difference from 1Pa·s